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FERRITE FOR THE ACCELERATING CAVITY OF NIMROD ITS ELECTRICAL PROPERTIES AND THEIR MEASUREMENTS

by

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1961

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ABSTRACT

The electrical properties specified for the ferrite for the accelerating cavity of Nimrod are quoted. Methods of measuring these properties are described for small test toroids and large cavity frames. Results of such measurements are given, and different grades of ferrite compared.

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February, 1961.

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1. INTRODUCTION

The accelerating unit of the 7 GeV Proton Synchrotron 'Nimrod' consists of a pair of re-entrant resonant cavities, loaded both inductively and capacitively and tunable over the required frequency range by an electrical signal. The resonant frequency is the fourth harmonic of the proton orbital frequency, and the cavity is required to be tunable from 1.2 to 8.1 Mc/s.

The inductive loading and the electrical tuning are both obtained by the use of ferrite cores in the cavities. The tuning is then performed by a biasing (or saturating) current in either an auxiliary winding, or in the cavity walls. The use of two cavities, wound in opposition, ensures that the bias current generator does not short circuit the radio-frequency source.

The ferrite introduces extra loss into the system, and the magnitude of this, which varies with the type and amount of ferrite used, must be balanced economically against the ease of tuning, the size and weight of the cavity and ferrite.

Owing to the limitations on the choice of cavity dimensions imposed by the overall machine design (vacuum chamber aperture and straight section length) and the predominance of ferrite loss over copper loss, the total radio-frequency and bias power requirements are almost entirely governed by the bulk properties of the ferrite.

These properties, listed in Section 2, had to be measured under the correct conditions of R.F. and D.C. flux. This is not normally done by the manufacturers as ferrite is not normally used under these conditions.

2. FERRITE SPECIFICATION (Electrical Properties Only)

2.1 The material is to be of Nickel-Zinc ferrite.

(Though Manganese-Zinc has a lower magnetostrictive constant, it has a dielectric constant so high ($\sim 10^4$) that dimensional resonances would certainly occur. Also Nickel-Zinc is the only commercially-produced type with reasonable Q-values at frequencies of 1 Mc/s and above).

2.2 The properties are to be measured after the material has been taken through a sufficient number of biasing cycles for the properties to be reproducible from cycle to cycle. A cycle is such that bias is applied linearly with time over a period of 0.35 seconds then removed and the process repeated every second.

The recovery time must be such that the specified ampere-turns are adequate for the cycle.

2.3 The material shall have a μQ greater than 5,000 at a frequency of 1.2 Mc/s and a peak radio-frequency induction (B_{RF}) of 60 gauss, with no external magnetic bias.

(The impedance of a parallel tuned circuit is :

$$Z = \omega L Q$$
$$= \omega L_o \mu Q$$

if L is an air-cored inductance of value L_o, filled with a material of relative permeability μ. Thus for given ω and Lo, the material parameter μQ of the ferrite is proportional to Z, and hence inversely proportional to the power required to maintain a specified voltage across the cavity. This figure, and those specified below, were arrived at after tests on samples to discover what could be expected, and consideration of the R.F. power and bias current supplies).

2.4 When the material is used to load a pure inductance which is then resonated at a frequency of 1.2 Mc/s by a pure capacitance, it must be possible to pull the resonant frequency to 8.1 Mc/s with an applied bias field of not more than 15 ampere-turns per centimetre, in the same direction as B_{RF}. This figure must include the effects of any joints.

2.5 During the frequency change, B_{RF} will decrease inversely with frequency to a value of 9 gauss. μQ must change smoothly, but must not fall below a value of 400 at 8.1 Mc/s.

2.6 The above properties are to be measured at a temperature of 20°C.

2.7 The incremental permeability at 60°C must not be less than 90% of the figure at 20°C, over the frequency range specified in Section 2.4 above.

2.8 The dielectric constant must be less than 20, and the total dielectric loss-factor must be less than 0.2 over the specified frequency range. The specific resistance must be greater than 0.2×10^6 ohm-cm. over the frequency range specified.

3. TEST CORES

A toroidal shape is most satisfactory for the measurement of magnetic properties of materials, and this was used for all the preliminary measurements of ferrite samples. Mean diameters varied from 2 to 8 cm., cross-sectional areas (rectangular) from 0.1 to 1.5 cm^2.

As the properties of a piece of ferrite depend critically on the exact physical treatment during manufacture (pressure, particle size, heat treatment etc.), it cannot be assumed that a large sample will have the same properties as a small one. Therefore, when the more suitable materials had been determined, fairly large slabs (12.5 x 10 x 2 cm.) were obtained and glued into "small frames" to check against the toroid results. These small frames were also used in model cavities.

A further check was carried out by cutting small toroids from some of the slabs, and measuring these in the normal way.

Finally, the actual cavity frames had to be tested on delivery. These were each made of 20 blocks (average size 25 x 23 x 4 cm.) glued together to form a frame with an aperture about 53 x 115 cm.

These different core sizes necessitated different winding configurations and rather different measurement techniques, which are described below.

4. μQ AND BIAS CURRENT MEASUREMENTS ON TOROIDS

4.1 Circuit Arrangements

The circuit is shown in Figure 1.

It is advisable not to use separate windings for the R.F. and D.C. currents, owing to the complex effects (including resonances within the 1-8 Mc/s band) of the mutual and self capacitances and inductances of the two windings. The D.C. and R.F. currents therefore use the same conductors, the two coils being connected in parallel for R.F. and series for D.C. as shown in Figure 1, to ensure zero R.F. pick-up in the D.C. circuit.

The choice of number of turns is important, and is discussed in detail below.

The impedance Z of the tuned circuit is given by:

$$Z/R = \frac{V_2}{V_1 - V_2}$$

Also, $Z = \frac{1}{2}\omega LQ = \pi f L_o \mu Q$ and $L_o = \mu_o N^2 . A/\ell$ in MKS units, where N = number of turns, A = cross-sectional area, ℓ = mean circumference of a toroid.

Hence: $$\mu Q = \frac{R}{\pi f \mu_o N^2 A} \cdot \frac{V_2}{V_1 - V_2}$$

The value of C (which will include stray capacitances of the second valve voltmeter and the coils) does not need to be known to obtain μQ. It can easily be estimated to give approximate values for μ and Q separately, when they are of interest.

The non-inductive carbon composition resistor should be comparable in value to Z, for accuracy, and small enough ($<10\ K\Omega$) for its stray capacity to be negligible at these frequencies. This can be checked by repeating a measurement with a resistor of different value but identical size.

The blocking capacitors are non-inductive mica.

The R.F. source is a signal generator followed by a wide-band amplifier giving up to 100 V into 5,000 Ω - sufficient to establish the correct B_{RF}.

The D.C. current source is transistor-controlled from a rectifier, giving excellent smoothing and control. A 12 amp. supply uses four V15/30P transistors in the output stage, and one as a driver.

Voltage measurements are by valve-voltmeters, checked for identity by always repeating the readings after interchanging the meters.

The filter must be used because of the possible serious effect, on V_1 only, of harmonic content. Filter and measuring circuits must be in separate screening cans. If high B_{RF} values are sustained for long periods, an oil-bath is necessary to keep the temperature constant.

4.2 Choice of Number of Turns

To get reliable results, with errors due to flux leakage kept small, it is necessary to use a large number of turns of fairly thick wire, or alternatively, a sheet winding.

It is necessary to keep the D.C. current and R.F. voltage requirements within the capabilities of the supplies, and to limit ohmic heating. The inductance must be such as to require a suitable resonating capacitor, not too low in relation to the strays.

20 to 30 turns of 18 to 22 S.W.G. wire were typical for most cores, with unbiased permeabilities of 600 and more. However, as μ is decreased, e.g. to 500, the ill effects of too few turns become rapidly noticeable under fully biased conditions, and up to 50 turns may have to be used.

There are two effects due to leakage, illustrated in Figure 2:-

(a) If the small number of turns are closely spaced on a small part of the core (Fig. 2a) the flux linking these turns will not all follow the full core path-length. The reluctance is effectively reduced, which makes μ appear greater. This means that to achieve the desired frequency range, a bias current greater than normal has to be applied, and under this condition Q is greater, so that the observed μQ is greater also.

(b) If the small number of turns is evenly spaced around the core, (Fig. 2b) the leakage means that there is incomplete coupling between turns. Thus, in the formula:

$$L = \mu N^x A/\ell$$

x is less than 2, tending to unity. This makes the effective μ smaller, so that a lower value of bias current is required, giving a lower value of μQ.

In carrying out the experiment, the procedure is as follows:-

(i) Cycle to maximum bias current several times.

(ii) Tune filter and test circuit for maximum readings on both voltmeters.
(The test circuit is tuned by capacity at zero bias, and by D.C. current at all higher frequencies).

(iii) Set V_2 to give the correct flux density.

(iv) Read both voltmeters and the D.C. ammeter.

5. RESULTS OF μQ AND BIAS CURRENT MEASUREMENTS ON TOROIDS

5.1 μQ

With the correct conditions of R.F. and D.C. flux densities, μQ is plotted against frequency in Figure 3 for the principal ferrites of interest.

There is a steady decrease in μQ, which, for a good ferrite, tends to follow the law:

$$\mu Q = Af^{-3/2}$$

5.2 Bias Current

Figure 4 shows the bias currents corresponding to the results in Section 5.1 above.

The curves show a smooth increase, with bias current approximately proportional to frequency at first, but at fairly low currents this approaches a quadratic law:

$$I_{DC} = B(f-f_o)^2$$

5.3 Effect of R.F. Flux Density (B_{RF})

Some typical curves showing the decrease of Q (unbiased) with increasing B_{RF} are shown in Figure 5. This is a property which varies considerably between samples, even of the same type.

5.4 Effect of Temperature

Almost up to the Curie Point, μ increases with temperature, and Q decreases. The net effect is a decrease in μQ of 1 to 1.5% per ^{o}C rise of temperature. Bias current decreases about 1% per ^{o}C rise. Typical graphs, for Philips 1387 sample, are shown in Figure 6.

6. FURTHER EXPERIMENTS

6.1 Recovery Time

Using the same circuit, the coil and signal generator were tuned to 1.2 Mc/s, and the envelope of the voltage across the coil monitored by an oscilloscope whilst a sawtooth bias current cycled the core. At the end of each sweep the current was reduced to zero instantaneously by a relay, and the time taken for the coil to return to resonance observed.

Typical oscillograms are shown in Figure 7. The recovery time is seen to be appreciable, but not significant for our purpose.

6.2 Dielectric Constant and Loss

Samples of ferrite were placed between the plates of a capacitor, and the resulting capacity and power-factor measured on a Q-meter at several frequencies.

(a) Toroidal Samples:

Sample 1 had a small value of δR, and so coaxial electrodes were used. Sample 2 was thinner, with a larger δR, so flat annular electrodes were better.

Results

Freq. (Mc/s)	Sample 1		Sample 2	
	K	tan δ	K	tan δ
2.4	14.2	0.0027	14.0	0.0215
3.5	"	0.0044	-	-
4.5	"	0.0039	14.0	0.0247
5.0	"	0.0052	"	0.0183
6.0	"	0.0070	"	0.0168
8.0	"	0.0120	"	0.0215

(b) Cavity Frames:

Two 4" x 3" flat plates were used as electrodes, on a large block of ferrite, 4 cm. thick. A correction was applied for fringing. It is clear from the first results that the slab was large enough for a dimensional resonance to be approached at the maximum frequency, and the experiment was repeated with full bias field applied to reduce the permeability.

Results

Freq. (Mc/s)	Unbiased			Biased		
	K	tan δ	$\lambda/4$ effective (cm.)	K	tan δ	Loss-Factor
1.0	-	-	86.(0)	14.4	0.0130	0.19
2.0	14.1	0.012	43.(0)	14.8	0.0110	0.16
4.0	14.8	0.04	21.(5)	14.4	0.0088	0.13
6.0	16.3	0.10	14.(4)	14.4	0.0086	0.13
8.0	18.4	0.23	10.(8)	15.2	0.0067	0.10
10.0	-	-	8.(6)	15.6	0.0095	0.15

7. SMALL FERRITE FRAMES

Impedance and bias current measurements were made as for the toroids. The circuit was the same, but the winding was a close-fitting single turn, or sheet winding, of the form and dimensions shown in Figure 8. It was necessary to use extremely low impedance paths both for connecting the tuning capacitors and for paralleling the toroids, due to the low inductances of the windings themselves.

Low power measurements only were done.

Rings were cut from some samples, and gave excellent agreement.

8. TESTING ACTUAL CAVITY FRAMES

8.1 Method of Measurement

The dimensions of a frame are shown in Figure 9, and a photograph in Figure 10. The frame is in four separate "limbs".

The parameters measured were: μ (at remanence); μQ at 1.2 Mc/s, as a function of B_{RF} to as high a value as possible; μQ at 8.1 Mc/s (which varies only slightly with B_{RF}) at a standard B_{RF}; and bias field.

For a core this size, the only winding which would avoid subsidiary resonances was a single-turn sheet winding, totally enclosing the core. The bias winding was a separate 30 turn, 200 amp. coil outside the R.F. sheet winding.

Figure 11 shows the electrical layout of the test rig. Figure 12 is a photograph of it. About 110 capacitors of 100 pF. each were used as tuning capacitors on each frame. These were distributed carefully in order to get a constant voltage at all points on the circumference at the highest frequency. Tuning was carried out by varying the number of these capacitors, and the stray capacitance (800 pF. per frame) was found from the intercept on a graph of C plotted against $1/f^2$.

The bias current was smoothed by a large choke giving a ripple less than 1% peak-to-peak.

The measuring circuit is shown in Figure 13. The radio-frequency voltage across the resonant circuit was measured directly by a valve voltmeter. To measure the R.F. current, in order to determine the impedance, a non-inductive shunt resistor, value 0.5Ω, was placed in the earthy side of the circuit. The voltage across this shunt was measured by a crystal rectifier and D.C. voltmeter. The system was calibrated using low-inductance resistors, whose impedances had been checked on a radio-frequency bridge.

The R.F. power was produced in a push-pull, broad-band amplifier capable of generating a few hundred watts. It was fed through a step-down, balance-to-unbalance, ferrite-cored transformer, followed by a low-pass filter.

8.2 Calculation of Results

A correction of + 4% had to be added to the measured value of μQ at 8.1 Mc/s. This is made up of 3% for loss in the capacitors, $<1\%$ ferrite dielectric loss, $<0.3\%$ due to ripple on the bias current.

The calculations use the following figures and relations:-

Outer circumference	:	ℓ_o	=	5.368 metres
Inner "	:	ℓ_i	=	3.368 "
Mean "	:	ℓ	=	4.368 "

Cross-sectional area A = 0.01 metre^2

Neglecting the correction for the difference between ℓ_o and ℓ_i we have:

$$\text{Inductance} \quad L = \mu L_o = \mu \frac{4\pi}{10^7} \cdot \frac{A}{\ell} \quad \text{Henry}$$

$$= \mu \times 2.88 \times 10^{-9} \text{ Henry}$$

$$\text{The correction to this is:} \quad L_o' = L_o \log_e \frac{\ell_o}{\ell_i} \Big/ 2\frac{\ell_o - \ell_i}{\ell_o + \ell_i} = 1.018\, L_o$$

$$\mu L_o' = 1/4\pi^2 f^2 C$$

Hence $\mu = \dfrac{5980}{C}$ at 1.20 Mc/s, (where C is in units of 10^3 pF. and is per frame).

Impedance, $Z = \frac{1}{2}\omega L_o' \mu Q$ (two frames in parallel)

$$= \pi f L_o' \mu Q$$

Whence, at 1.20 Mc/s: $\mu Q_{1.2} = 90.6\ Z$

at 8.10 Mc/s: $\mu Q_{8.1} = 13.4\ Z$

The R.F. flux density may be obtained from:

$V_{RMS} = 0.0444 f N A \hat{B}$ volts, (where f is in Mc/s, A is in cm.^2, and $\hat{B}$ is in gauss).

Hence at 1.20 Mc/s we have:

$$\hat{B}_{RF} = 0.187\ V_{RMS}$$

$$\text{Bias field} = \frac{I_{DC}\ N_{DC}}{\ell} = 0.0687\ I_{DC} \text{ amp.-turns/cm.}$$

8.3 Results

The mean values, and maximum variations from these, for the 34 frames were:-

(a) Initial Permeability (at remanence):

$$\mu = 557 \pm 13\%$$

(b) μQ at 1.2 Mc/s = 6230 $\pm$ 22% (60 gauss)

$$\therefore \; Q_{1.2} = 11.2$$

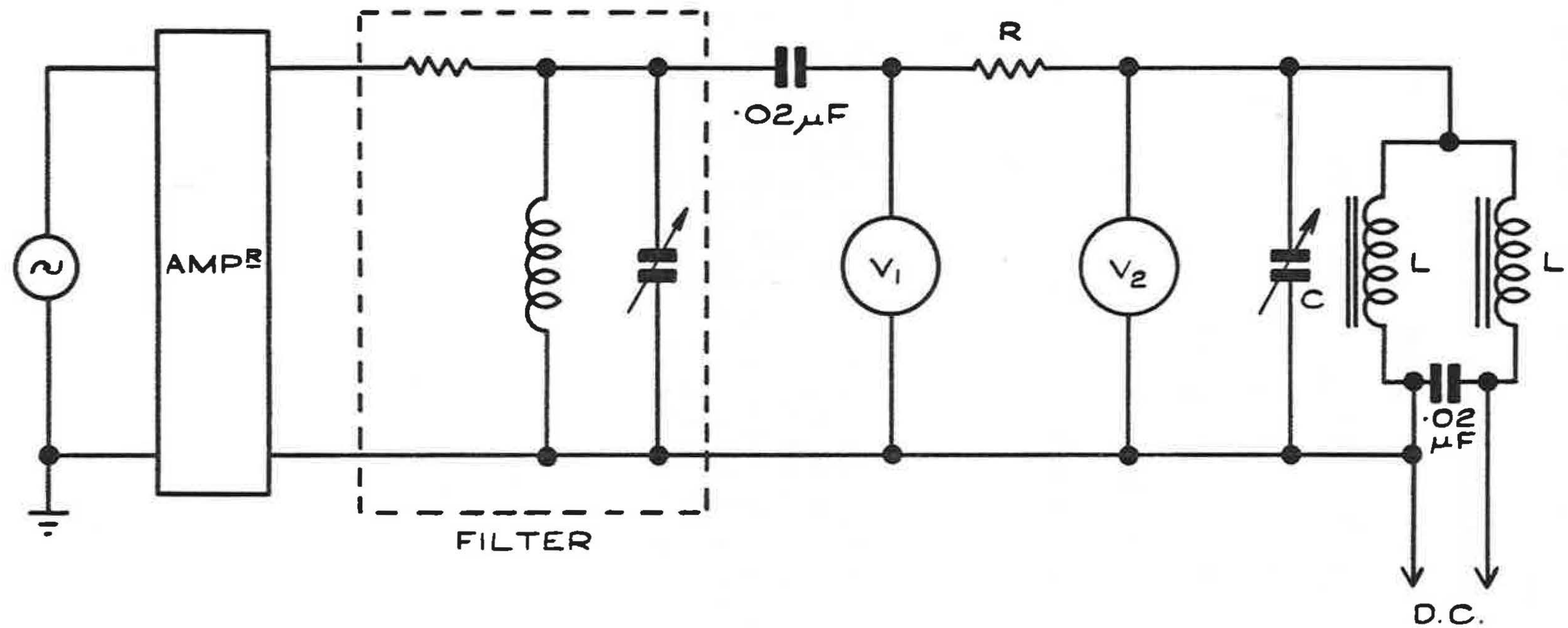
(c) μQ at 8.1 Mc/s = 490 $\pm$ 20%

$$\therefore \; Q_{8.1} = 40$$

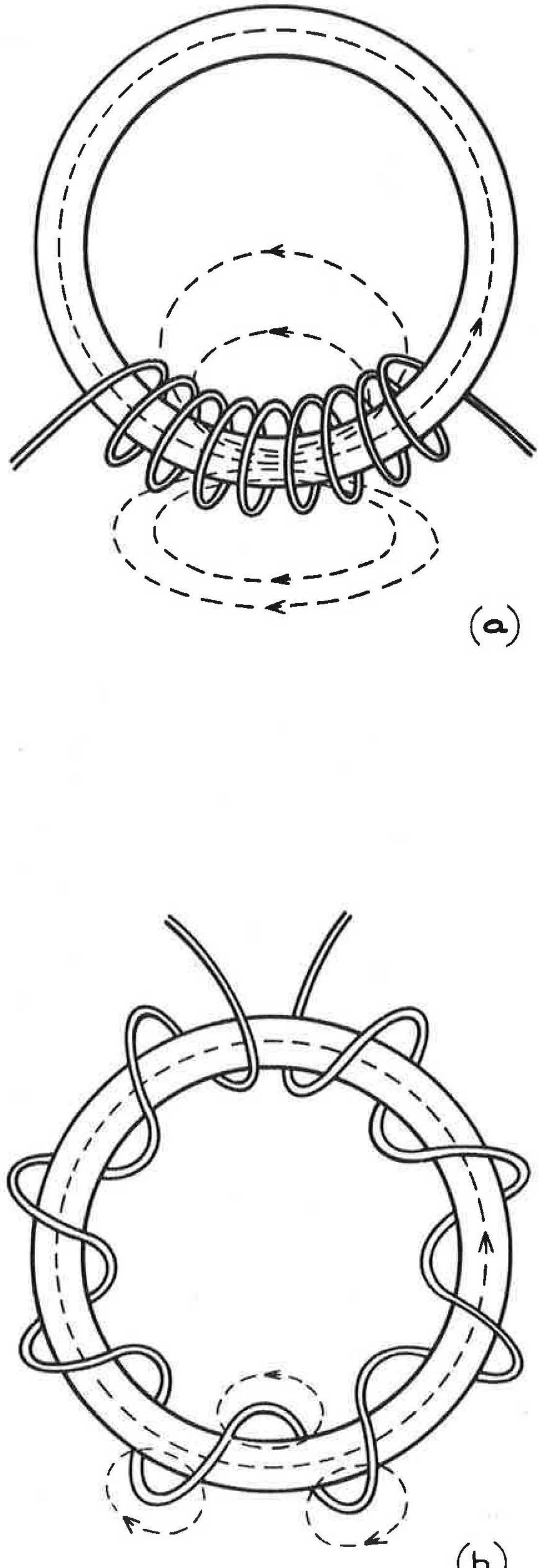
(d) Field for biasing to 8.1 Mc/s = 10.7 amp.-turns per cm. $\pm$ 19%

9. SUMMARY

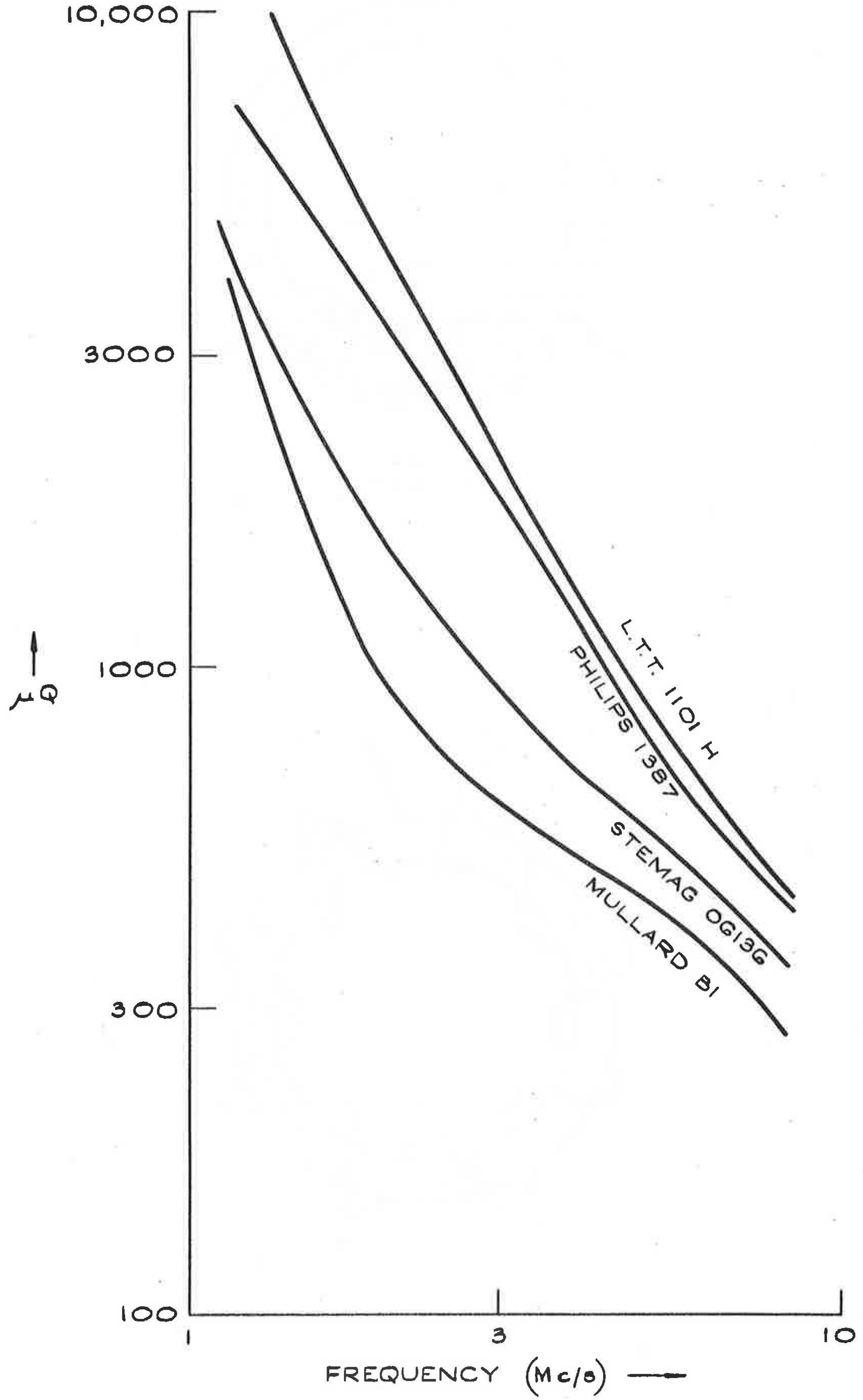
Methods have been described for measuring the electrical properties of ferrite material under the conditions which apply in the accelerating cavity of Nimrod. In particular, winding configurations have been found which give reliable results on the various core shapes encountered, and which enable the D.C. bias fields to be applied. The results of measurements on toroids indicated the typical properties of ferrites, and guided the composition of the specification. Measurements on the final product confirmed that it did meet the specification, and allowed the accurate prediction of the behaviour of the cavity.



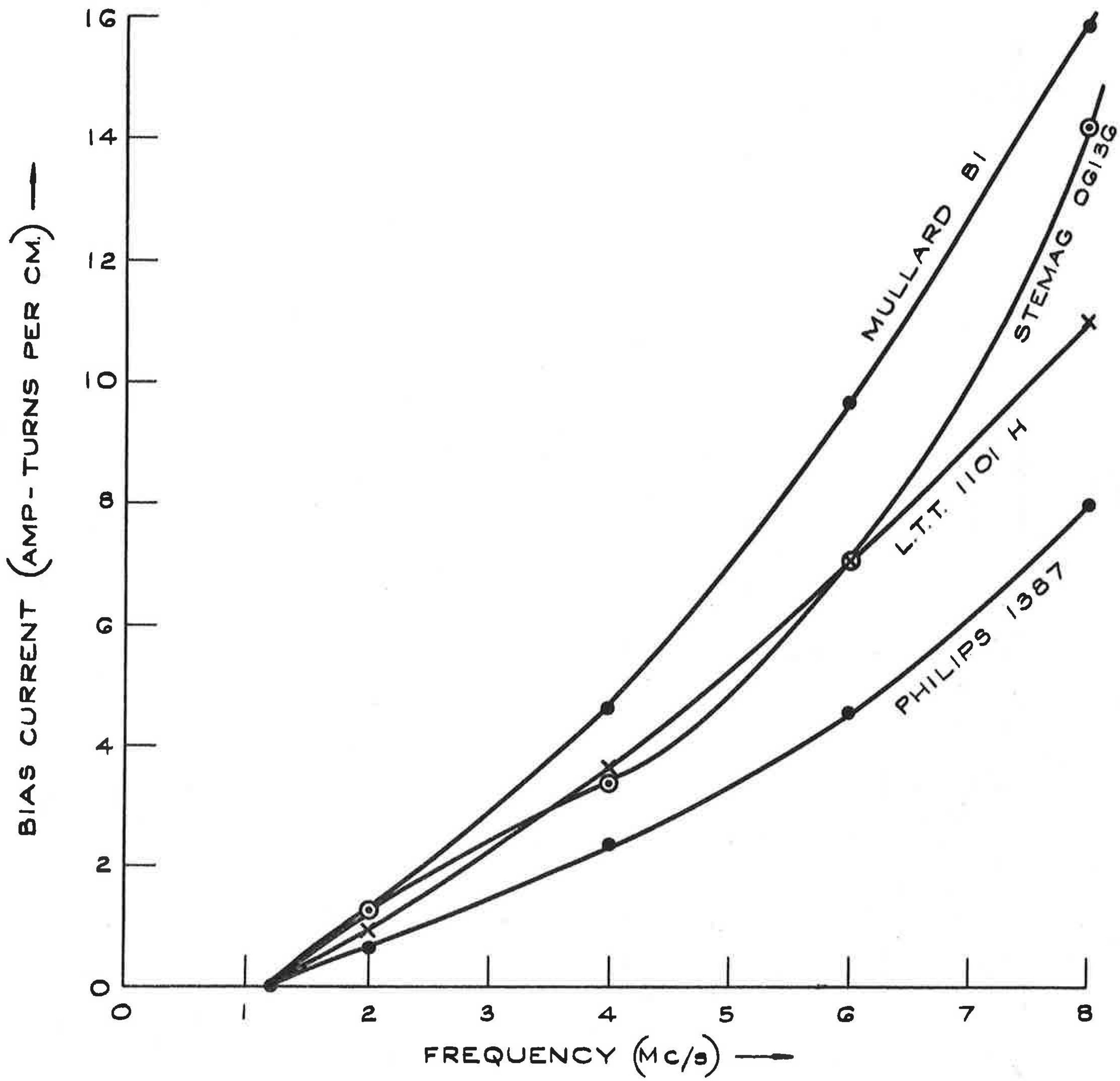
NIRL/R/5. FIG. I. CIRCUIT FOR TESTING TOROIDS.



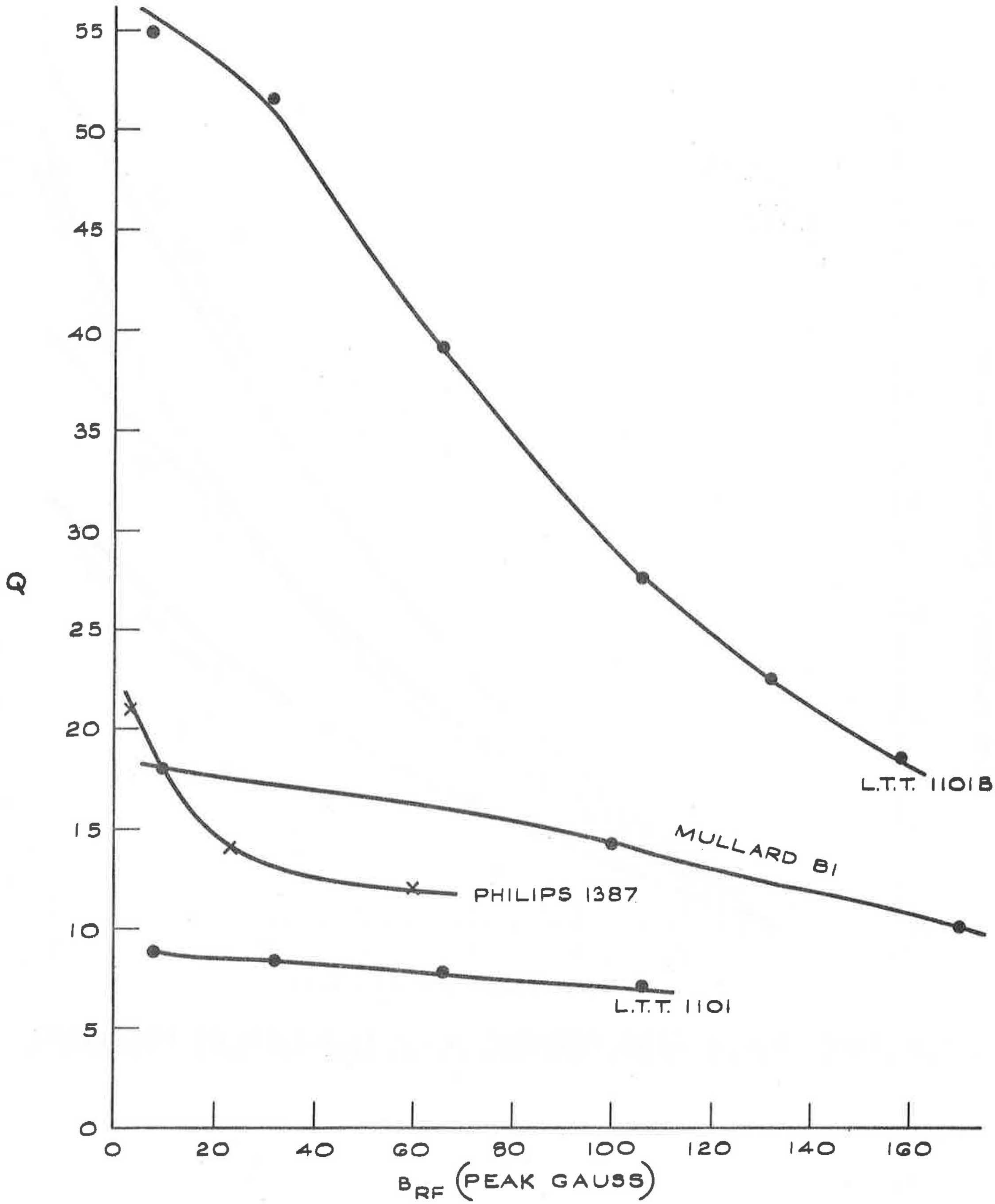
NIRL/R/5. FIG. 2. LEAKAGE FIELDS IN TOROIDS.



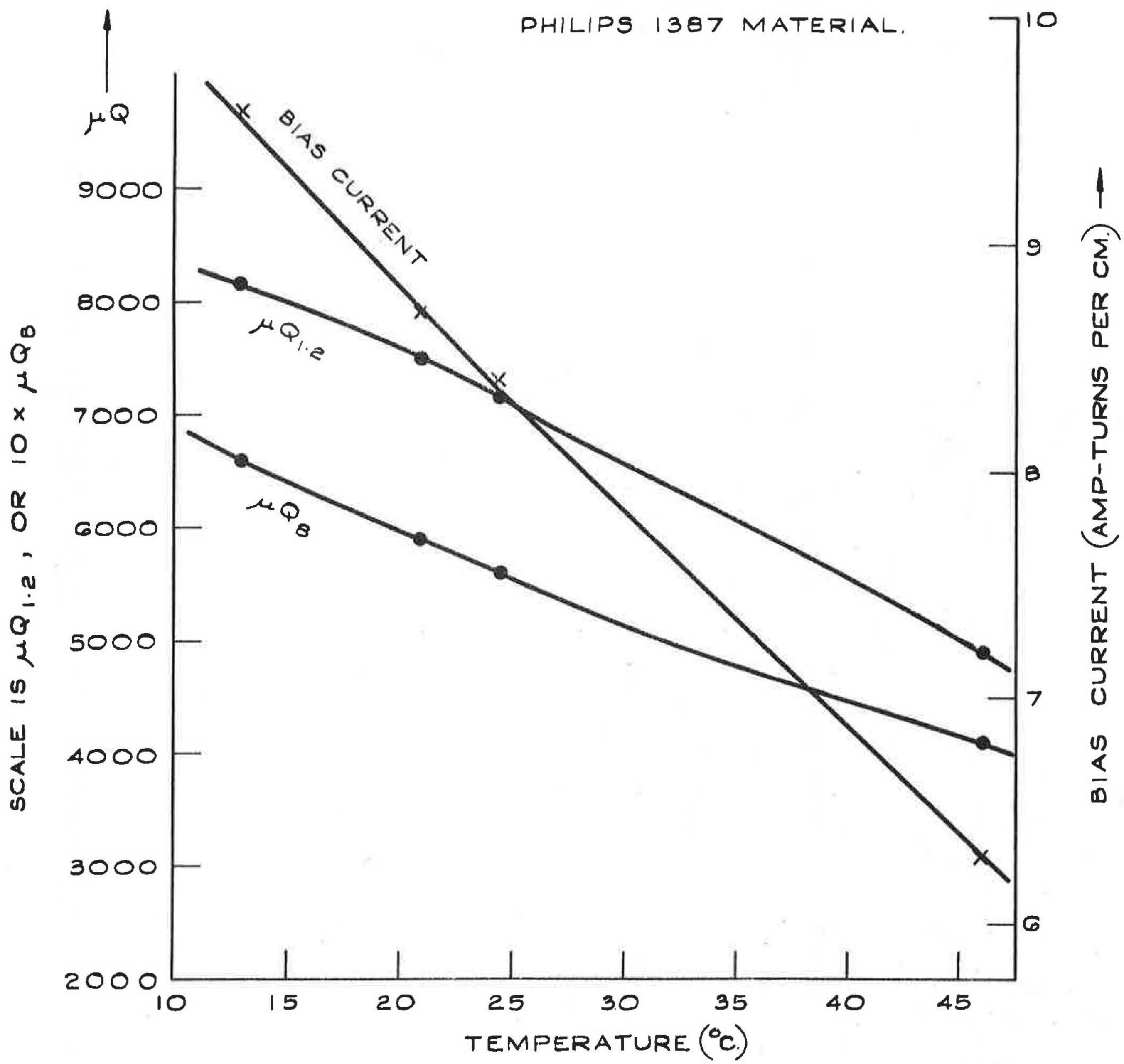
NIRL/R/5. FIG. 3. μQ AS A FUNCTION OF FREQUENCY.



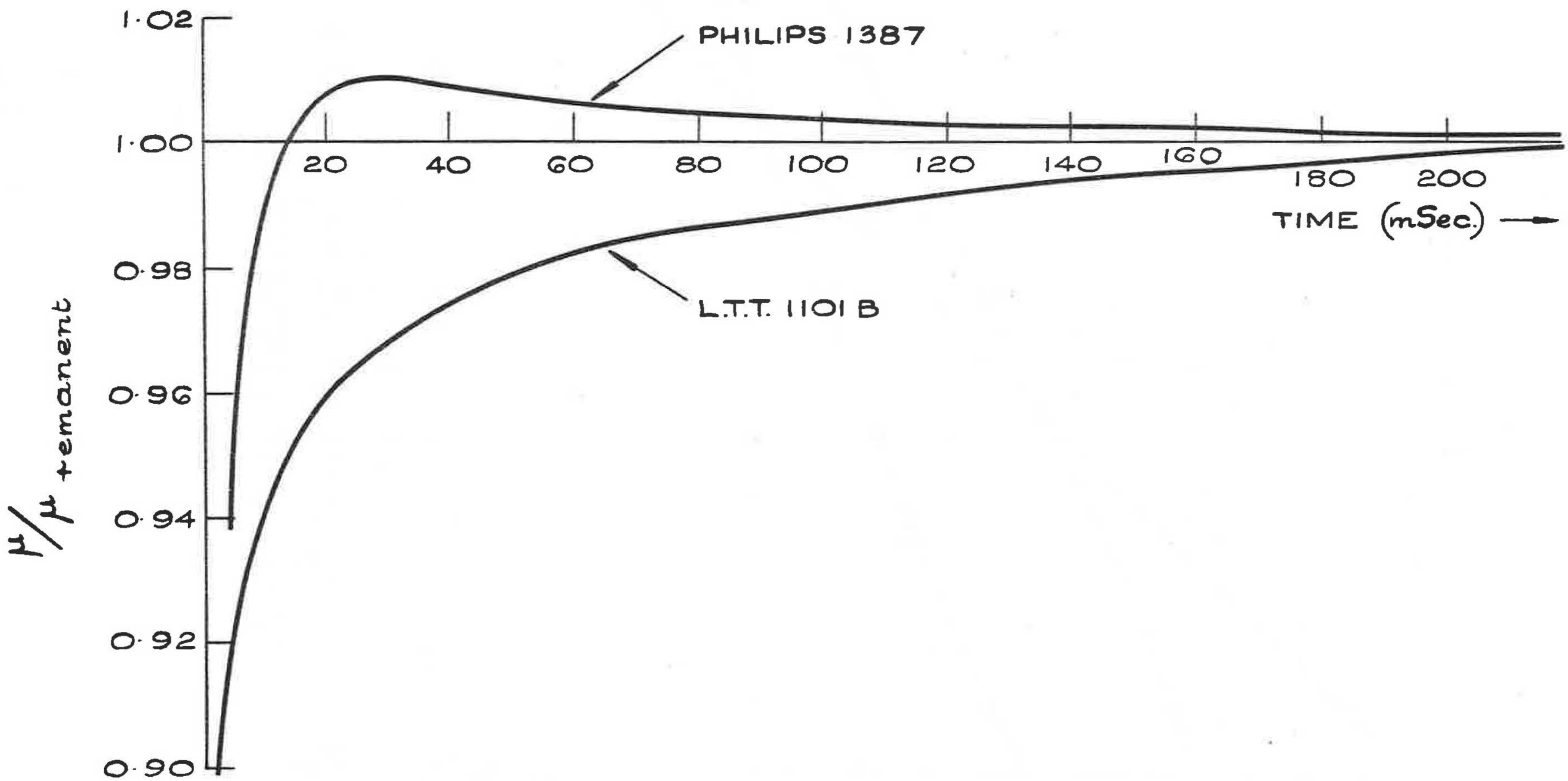
NIRL/R/5. FIG. 4. BIAS CURRENT AS A FUNCTION OF FREQUENCY.



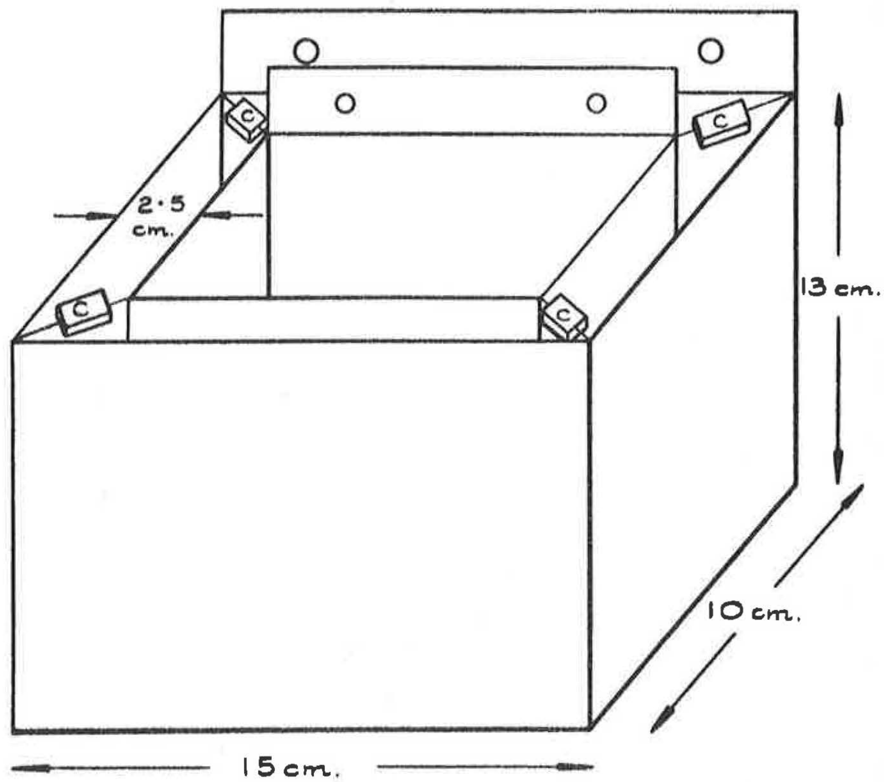
NIRL/R/5. FIG. 5. VARIATION OF Q AT 1·2 Mc/s WITH R.F. FLUX DENSITY.



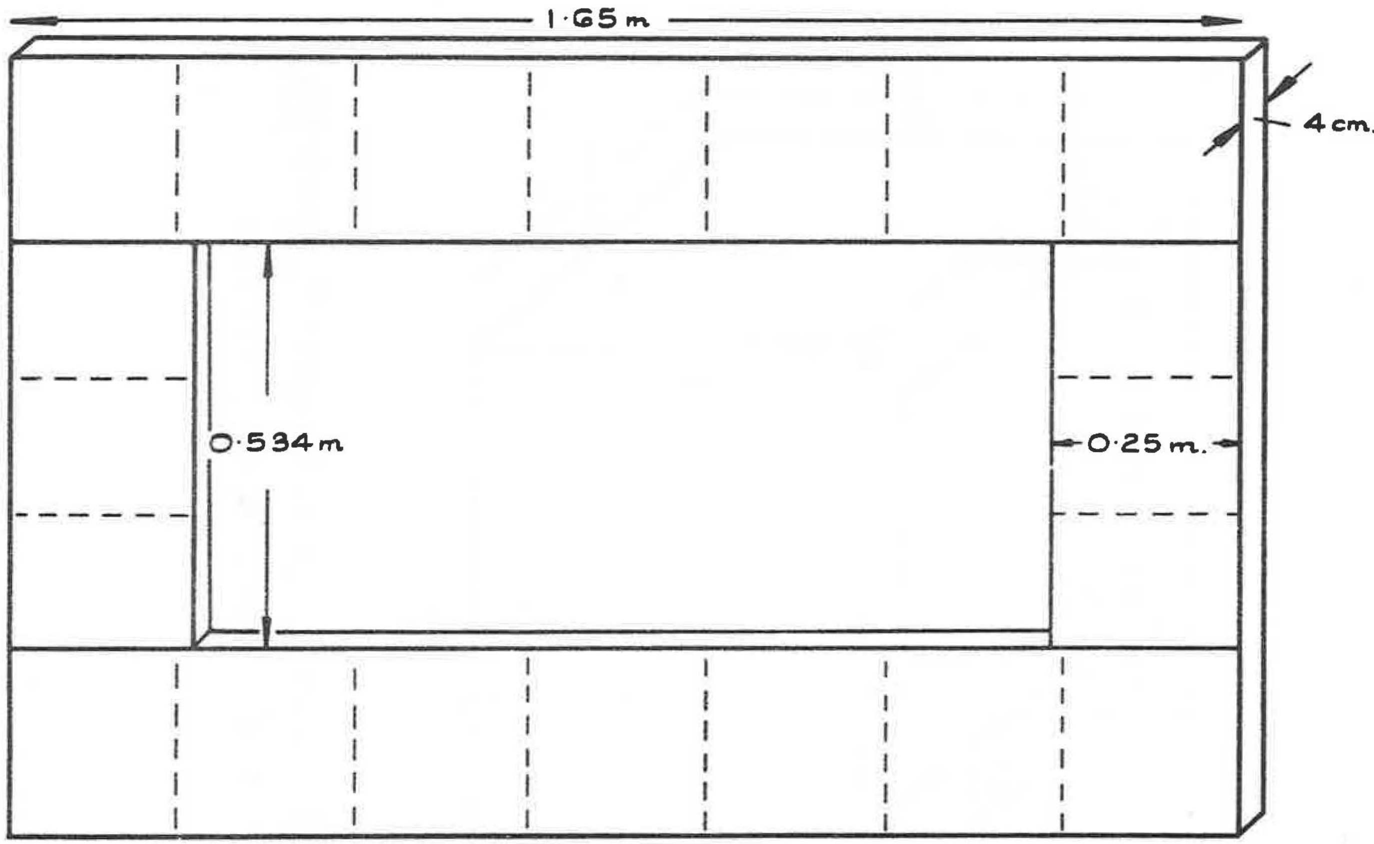
NIRL/R/5. FIG. 6. VARIATION OF $\mu Q_{1.2}$, μQ_8, AND BIAS CURRENT WITH TEMPERATURE.



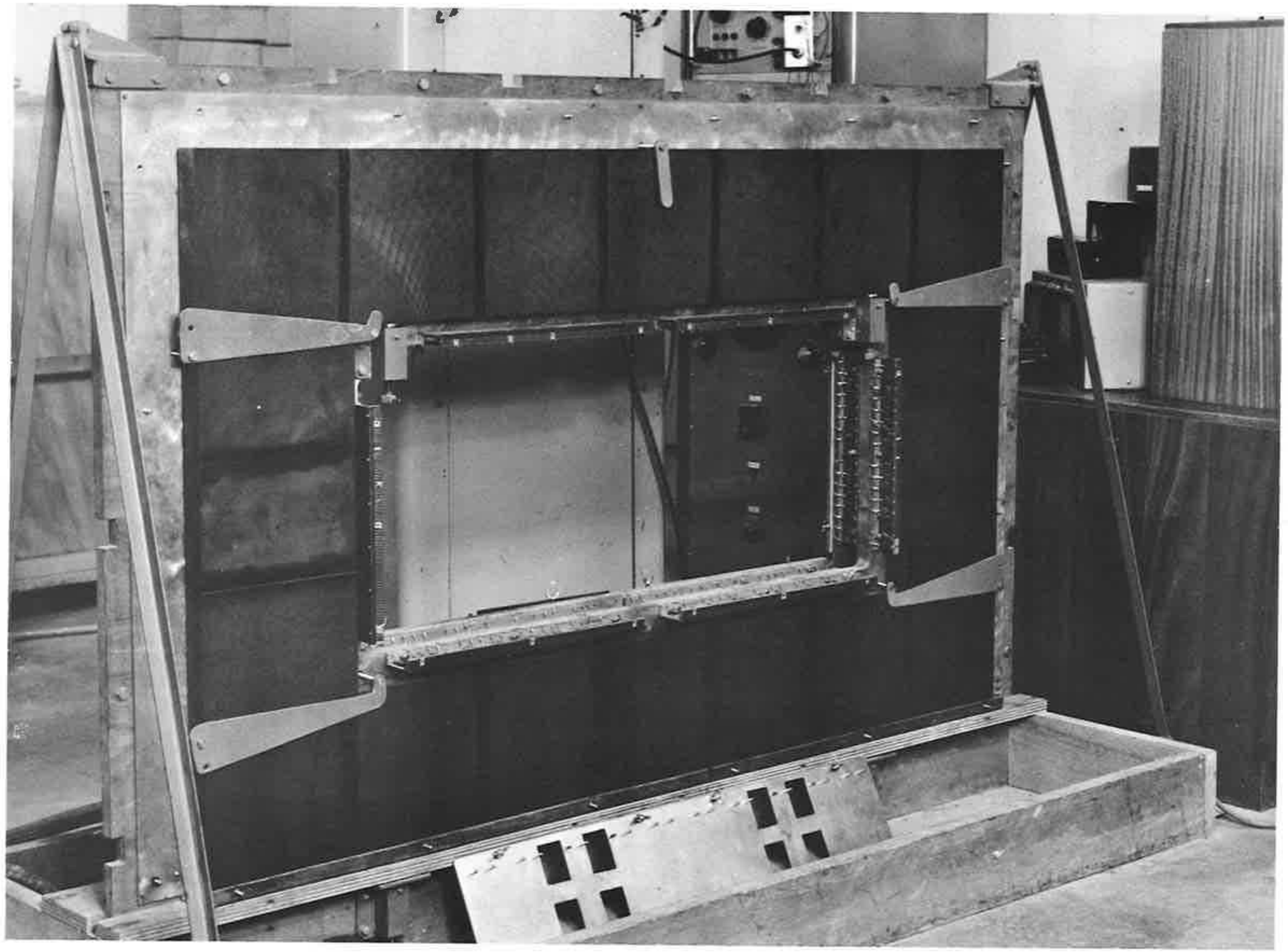
NIRL/R/5. FIG. 7. RECOVERY TIME FOR TWO SAMPLE TOROIDS.



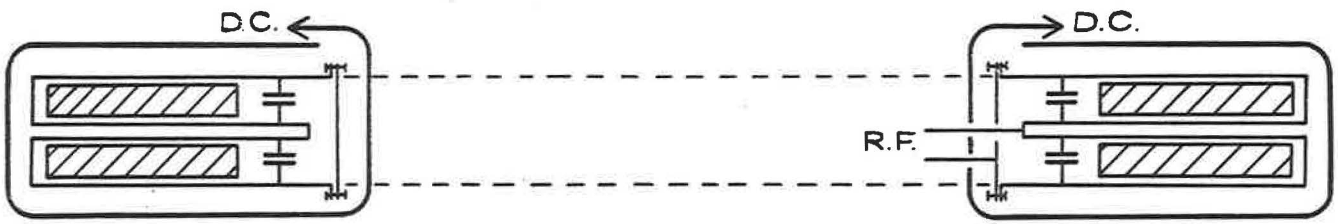
NIRL/R/5. FIG. 8. SHEET WINDING, FOR SMALL BLOCK TESTING.



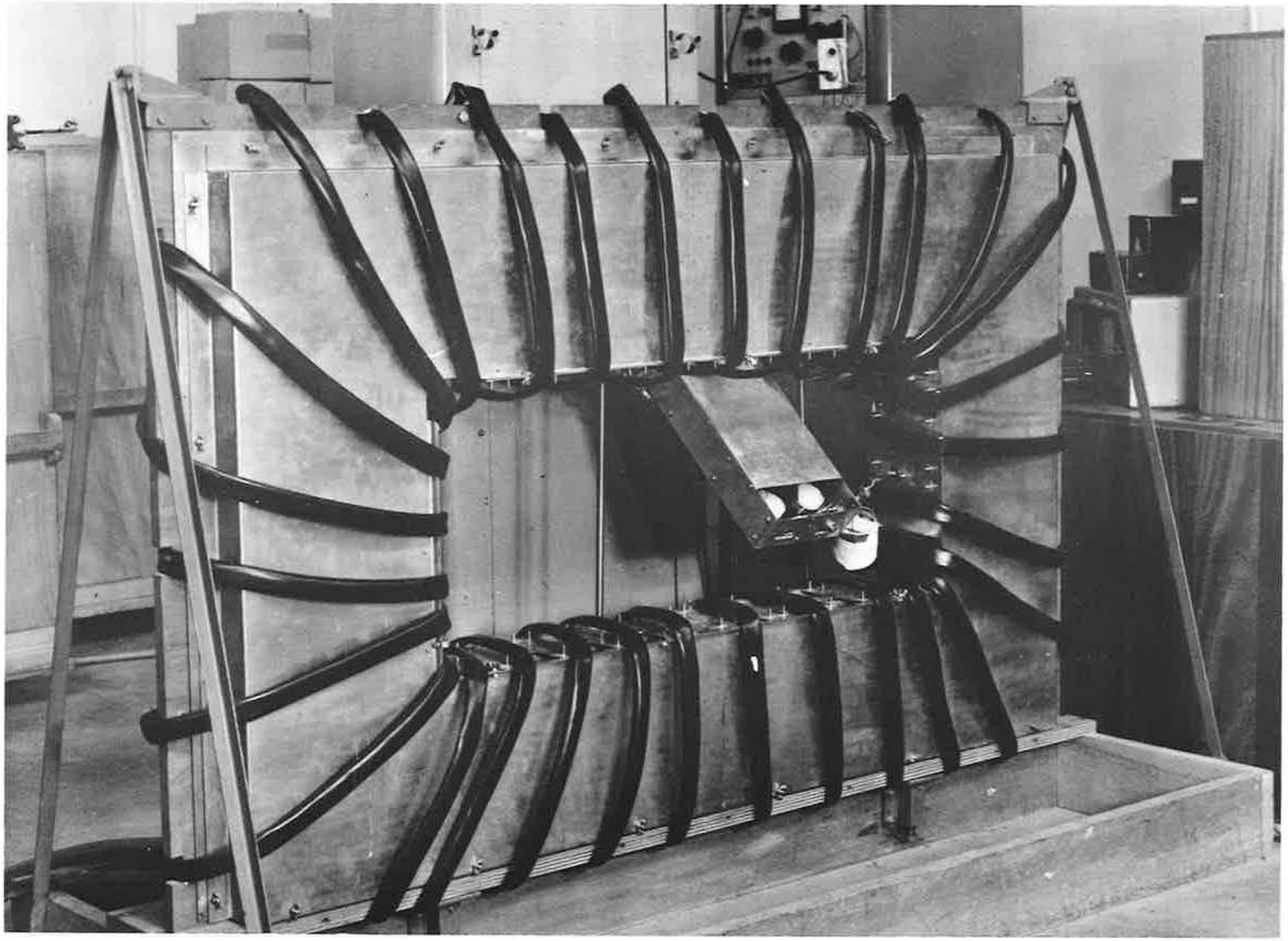
NIRL/R/5. FIG. 9. A FULL-SIZE FERRITE FRAME.



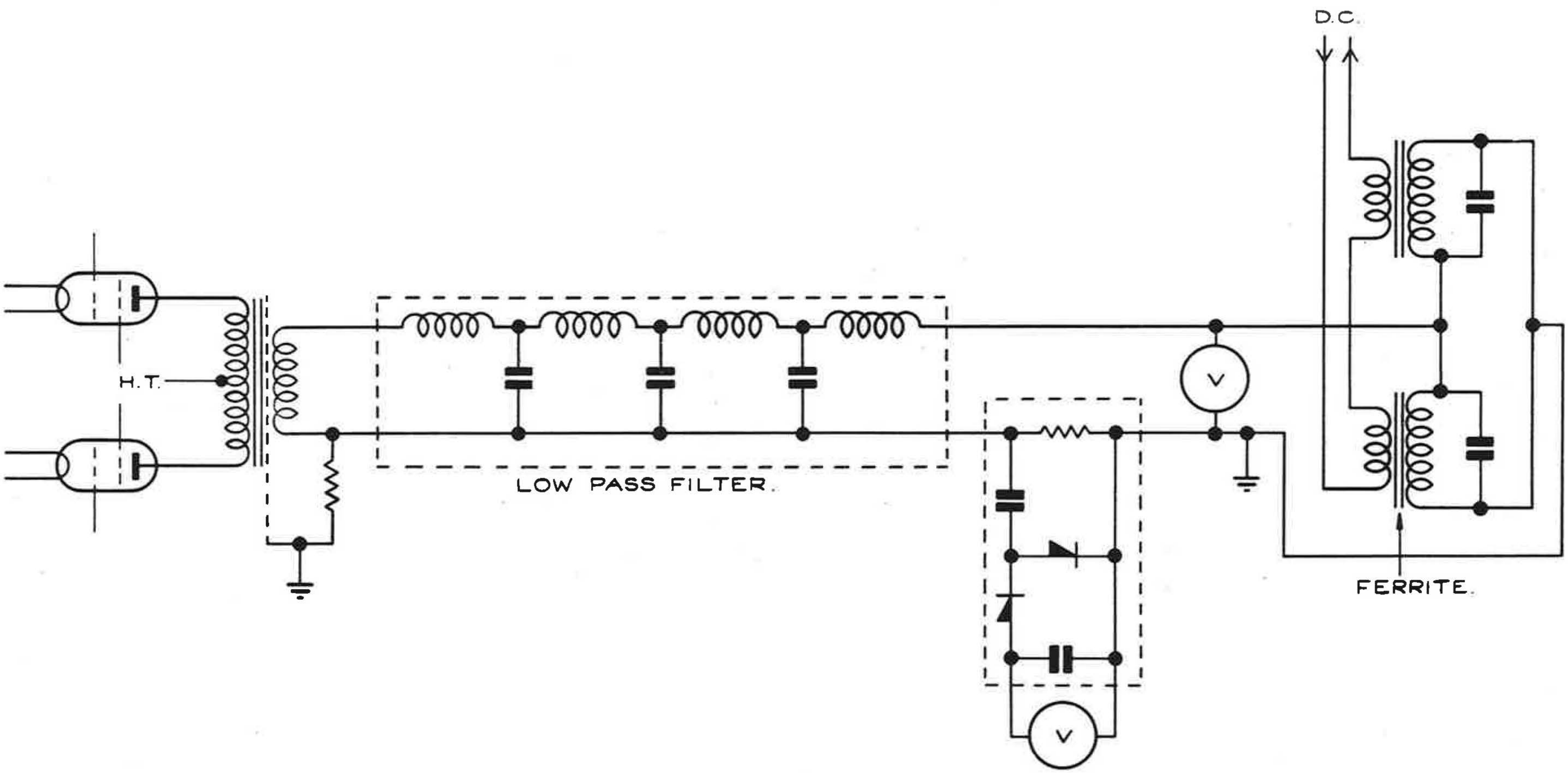
NIRL/R/5 FIG. 10. A FERRITE FRAME, IN THE TEST RIG.



NIRL/R/5. FIG. 11. SECTION THROUGH FERRITE TEST RIG.



NIRL/R/5 FIG. 12. THE COMPLETE TEST RIG.



NIRL / R / 5. FIG. 13. THE CIRCUIT USED FOR MEASUREMENTS ON FRAMES.

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